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13. ABSTRACT (Maximum 200 words) The research performed under this grant is summarized. In one component of the research, robust algorithms for signal processing with fractal signals were developed using wavelet-based representations. In a second component of the research, algorithms for addressing problems of detection, estimation and modeling using nonlinear and chaotic signals were developed. Finally, in a third component of the research, efficient algorithms for signal enhancement and active noise cancellation were developed. The resulting algorithms are promising candidates for a host of defense and related applications.			19960320 088	
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Final Report for AFOSR
Signal Analysis, Synthesis and Processing
Using Fractals and Wavelets

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1 Summary of Results from Research

The research under this grant explored signal processing algorithms for a broad range of applications relevant to the needs of the Department of Defense in general, and the Air Force in particular. This work is extensively documented in numerous publications and several student theses, both Masters' and PhD. A comprehensive list of these publications and theses is provided in Section 2.

1.1 Signal Processing with Fractals and Wavelets

One component of the research explored and developed the use of self-similar and fractal random processes as models for a wide range of natural and man-made phenomena. Natural and extremely efficient representations for such processes were developed out of orthonormal wavelet theory. These representations, in turn, led to powerful algorithms for addressing fundamental problems of detection and estimation involving such processes.

Algorithms for generating rich classes of deterministic signals with self-similar and fractal characteristics were also developed for applications ranging from remote sensing to communications. For the communications applications specifically, we demonstrated how the use of fractal signals leads to a novel diversity strategy, which we referred to as "fractal modulation", that was well suited to certain classes of unreliable channels. Fractal modulation also represents a potentially promising for secure communication in a variety of scenarios.

Subsequent work in this area explored richer modeling frameworks based on generalized classes of fractal signals, and efficient modeling algorithms were developed. In addition, preliminary work was performed that explored efficient multiscale models for nonGaussian fractal processes. A principle focus within this component of the research was on fractal point processes, which are important models for a wide range of phenomena ranging from auditory neuron firings in the human ear to vehicular traffic and data network traffic. For these processes, we developed extremely efficient synthesis and analysis algorithms based on a multiscale Poisson process framework. In addition, these multiscale Poisson-based representations allowed a number of important detection and estimation problems that involve fractal point processes to be addressed.

1.2 Signal Processing with Nonlinear/Chaotic Signals and Systems

This research explored the use of signals arising out of the theory of nonlinear dynamics and chaos for a variety of signal processing applications. One aspect of this research involved the development of chaotic modeling algorithms for physical signals. These included some promising new classes of nonlinear autoregressive modeling techniques. A particular emphasis within this research was on robust algorithms. For example, techniques for detection, estimation, and modeling in the presence of both additive and convolutional distortion were explored in detail, and important new classes of recursive filtering and blind deconvolution algorithms for chaotic signals were developed.

The research also explored the development of discrete-time signal models based on iterated nonlinear maps. A powerful framework for synthesizing and analyzing such signals was developed, and led to some potentially important results. For example, broad classes of nonlinear signal models with rational spectra were developed, with rich potential applications where linear models have traditionally been used. Optimum detection and estimation algorithms with highly efficient recursive implementations were also developed for the subclass of signals we refer to as "chaotic white noise".

In addition, the synthesis of chaotic signals for use in communications applications was also explored. In particular, classes of self-synchronizing chaotic systems were developed that have potentially promising characteristics for secure communications applications. A detailed analysis of these systems was performed. Finally, preliminary work on the use of soliton signal models and algorithms for signal processing and communications applications was performed, with encouraging results.

1.3 Algorithms for Signal Enhancement and Active Noise Cancellation

During the period of this grant we developed a number of new algorithms for signal enhancement and for active noise cancellation for both single-sensor and multiple sensor systems. One class of multiple sensor algorithms for signal enhancement is based on modifying the E-M algorithm for jointly estimating the desired signal, the coupling systems, and the unknown signal and noise spectral parameters. The resulting algorithms take the form of either iterative or sequential time-domain algorithms. A computationally efficient implementation was developed by exploiting the structure of the underlying equations. A very different approach to multiple sensor enhancement has also been developed. This second approach is based on separating decorrelated signals. The transfer function matrix of the processor is then designed to decorrelate the sensor inputs.

In the context of active noise cancellation, a new single sensor and a new two-sensor algorithm have been developed. In the single sensor algorithm, the noise field is modeled as a stochastic process and the parameters of the process are adaptively estimated. Based on these parameter estimates a canceling signal is generated. The algorithm was evaluated with both artificially generated noise and with recordings of aircraft noise. In common two-sensor approaches to active noise cancellation, a primary microphone is placed at the point where noise cancellation is desired and a secondary microphone placed at a location which provides a correlated measurement of the noise. In most existing ANC systems, the cancelling signal is derived only from the output of the secondary sensor. In our work we generate the cancelling signal based on the outputs of both the secondary and primary sensors. Specifically, we construct the cancelling signal as a linear combination of the past values of the outputs of all the sensors and use a two-input/single-output LMS algorithm to maximize the noise attenuation. This new algorithm provides a significant improvement over the conventional approaches to active noise cancellation.

2 Publications

2.1 Books & Book Chapters

- [1] A.V. Oppenheim and S.H. Nawab, editors of *Symbolic and Knowledge Based Signal Processing*, published by Prentice Hall, Englewood Cliffs, NJ, as part of the Signal Processing Series, 1992. Also a chapter in the book by A.V. Oppenheim (with others) "Computer-aided Algorithm Design and Rearrangement", pages 30-87.
- [2] Kevin M. Cuomo and Alan V. Oppenheim, "Analysis, Synthesis, and Applications of Self-Synchronizing Chaotic Systems," in *Nonlinear Dynamics in Circuits*, to be published as part of a book, the publisher being World Scientific Publishing Co. PTE. LTD.
- [3] A.V. Oppenheim, K.M. Cuomo, R.J. Barron, and A.E. Freedman, "Channel Equalization for Communication with Chaotic Signals," to be published as part of a book, the publisher being World Scientific Publishing Co. PTE. LTD.
- [4] Gregory W. Wornell, *Signal Processing with Fractals: A Wavelet-Based Approach*, Prentice Hall, Upper Saddle River, NJ, 1995.

2.2 Journal Articles

- [1] G.W. Wornell and A.V. Oppenheim, "Estimation of Fractal Signals from Noisy Measurements using Wavelets," *IEEE Transactions on Signal Processing*, Vol. 40, No. 3, pp. 611-623, March 1992.
- [2] G.W. Wornell and A.V. Oppenheim, "Wavelet-Based Representations for a Class of Self-Similar Signals with Application to Fractal Modulation," *IEEE Transactions on Information Theory*, Vol. 38, No. 2, pp. 785-800, March 1992.
- [3] K.M. Cuomo and A.V. Oppenheim, "Circuit Implementation of Synchronized Chaos with Applications to Communications," in *Physical Review Letters*, Vol. 71, No. 1, pp. 65-68, July 5, 1993.
- [4] K.M. Cuomo, A.V. Oppenheim and S.H. Strogatz, "Synchronization of Lorenz-Based Chaotic Circuits, with Applications to Communications," in *IEEE Transactions on Circuits and Systems*, Vol. 40, No. 10, pp. 626-633, October 1993.
- [5] E. Weinstein, M. Feder and A.V. Oppenheim, "Multi-Channel Signal Separation Based on Decorrelation," in *IEEE Transactions on Signal Processing*, Vol. 1, No. 4, pp. 405-413, October 1993.
- [6] G.W. Wornell, "Wavelet-Based Representations for the $1/f$ Family of Fractal Processes," in *Proceedings of the IEEE*, Vol. 81, No. 10, pp. 1428-1450, October 1993.
- [7] K.M. Cuomo, A.V. Oppenheim and S.H. Strogatz, "Robustness and Signal Recovery in a Synchronized Chaotic System," in *International Journal of Bifurcation and Chaos*, Vol. 3, No. 6, pp. 1629-1638, December 1993.

- [8] K.M. Cuomo, "Synthesizing Self-Synchronizing Chaotic Systems," in *International Journal of Bifurcation and Chaos*, Vol. 3, No. 5, pp. 1327-1337, October 1993.
- [9] Alan V. Oppenheim, E. Weinstein, K. Zangi, M. Feder and D. Gauger, "Single-Sensor Active Noise Cancellation," in *IEEE Transactions of Speech and Audio Processing*, Vol. 2, No. 4, pp. 285-290, April 1994.
- [10] Ehud Weinstein, Alan V. Oppenheim, Meir Feder and John Buck, "Iterative and Sequential Algorithms for Multi-Sensor Signal Enhancement," in *IEEE Transactions on Signal Processing*, Vol. 42, No. 3, pp. 846-859, April 1994.
- [11] A.C. Singer, G.W. Wornell, and A.V. Oppenheim, "Nonlinear Autoregressive Modeling and Estimation in the Presence of Noise," in *Digital Signal Processing*, Vol. 4, pp. 207-221, October 1994.
- [12] Haralabos C. Papadopoulos and Gregory W. Wornell, "Maximum Likelihood Estimation of a Class of Chaotic Signals," in *IEEE Trans. Inform. Theory*, Vol. 41, no. 1, pp. 312-317, January 1995.
- [13] G.W. Wornell, "Some Applications of Multirate Signal Processing and Wavelets in Wireless Communications," submitted May 1995 to *Proc. IEEE*, Special Issue on Applications of Wavelets (invited paper).
- [14] S.H. Isabelle and G.W. Wornell, "Statistical Analysis and Spectral Estimation Techniques for One-Dimensional Chaotic Signals," submitted Aug. 1995 to *IEEE Trans. Signal Processing*.
- [15] Gregory W. Wornell, "Spread-Signature CDMA: Efficient Multiuser Communication in the Presence of Fading," in *IEEE Trans. Inform. Theory*, Vol. 41, No. 5, pp. 1418-1438, Sept. 1995.
- [16] Warren M. Lam and Gregory W. Wornell, "Multiscale Representation and Estimation of Fractal Point Processes," to appear in *IEEE Trans. Signal Processing*, Vol. 43, No. 11, November 1995.
- [17] Gregory W. Wornell, "Spread-Response Precoding for Communication over Fading Channels," to appear in *IEEE Trans. Inform. Theory*, March 1996.

2.3 Conference Papers

- [1] G.W. Wornell and A.V. Oppenheim, "Representation, Synthesis, and Processing of Self-Similar Signals," in *Proc. Bienn. ASSP Mini-Conf.*, Boston, April 1991.
- [2] G.W. Wornell, "Communication over Fractal Channels," in *1991 IEEE International Conference on Acoustics, Speech and Signal Processing*, Vol. III, pp. 1945-1948, May 1991.
- [3] A.V. Oppenheim, E. Weinstein, K. Zangi, M. Feder and D. Gauger, "Single-Sensor Active Noise Cancellation using the EM Algorithm," in *1992 IEEE International Conference on Acoustics, Speech and Signal Processing*, Vol. I, pp. 277-280, April 1992.

- [4] A.C. Singer, G.W. Wornell and A.V. Oppenheim, "Codebook Prediction: A Nonlinear Signal Modeling Paradigm," in *1992 IEEE International Conference on Acoustics, Speech and Signal Processing*, Vol. V, pp. 325-328, April 1992.
- [5] S.H. Isabelle, A.V. Oppenheim and G.W. Wornell, "Effects of Convolution on Chaotic Signals," in *1992 IEEE International Conference on Acoustics, Speech and Signal Processing*, Vol. IV, pp. 133-136, April 1992.
- [6] A.V. Oppenheim, G.W. Wornell, S.H. Isabelle and K.M. Cuomo, "Signal Processing in Context of Chaotic Signals," in *1992 IEEE International Conference on Acoustics, Speech and Signal Processing*, Vol. IV, pp. 117-120, April 1992.
- [7] G.W. Wornell and W.W. Lam, "Spectral Analysis on a Log-Frequency Scale and Modeling of Scaling Behaviour in Fractal Signals," in *Proc. 5th DSP Workshop*, Sept. 1992.
- [8] K.M. Cuomo and A.V. Oppenheim, "Chaotic Signals and Systems for Communications," in *1993 International Conference on Acoustics, Speech and Signal Processing*, Vol. III, pp. 137-140, (Minneapolis, MN), April 1993.
- [9] H. Papadopolous and G.W. Wornell, "Optimal Detection of a Class of Chaotic Signals," in *1993 International Conference on Acoustics, Speech and Signal Processing*, Vol. III, pp. 117-120, (Minneapolis, MN), April 1993.
- [10] M.D. Richard, "Properties and Discrimination of Chaotic Maps," in *1993 IEEE International Conference on Acoustics, Speech and Signal Processing*, Vol. III, pp. 141-144, (Minneapolis, MN), April 1993.
- [11] K. Zangi and A.V. Oppenheim, "A New Two-Sensor Algorithm for Active Noise Cancellation," in *em 1993 IEEE International Conference on Acoustics, Speech and Signal Processing*, Vol. II, pp. 351-354, (Minneapolis, MN), April 1993.
- [12] A.V. Oppenheim, H. Nawab, G. Verghese, and G.W. Wornell, "Algorithms for Signal Processing," in *Proc. Annual Conf. on Rapid Prototyping of Application-Specific Signal Processors*, Arlington, VA, pp. 1465-1553, August 1994. (invited)
- [13] Warren W. Lam and Gregory W. Wornell, "Multiscale Synthesis and Analysis of Fractal Renewal Processes," in *1994 Proc. Digital Signal Processing Workshop*, October 1994.
- [14] Gregory W. Wornell, "A New Class of CDMA Systems for Fading Channels," in *Proc. IEEE Workshop on Information Theory, Multiple Access and Quering*, April 1995.
- [15] John R. Buck, James C. Preisig, Mark Johnson and Josko Catipovic, "Monochromatic Single-Mode Excitation in Shallow Water Using Feedback Control," in *Proc. ICASSP 95*, Vol. 5, pp. 3107-3110, May 1995.
- [16] Steven H. Isabelle and Gregory W. Wornell, "Statistical Properties of One-Dimensional Chaotic Signals," in *Proc. ICASSP 95*, Vol. 2, pp. 1352-1355, May 1995.
- [17] Andrew C. Singer, "Signaling Techniques Using Solitons," in *Proc. ICASSP 95*, Vol. 2, pp. 1336-1339, May 1995.

- [18] Warren M. Lam and Gregory W. Wornell, "Multiresolution Representations and Algorithms for Fractal Point Processes," in *1995 Proc. IEEE Workshop on Nonlinear Signal and Image Processing*, June 1995. (invited)
- [19] Andrew C. Singer, "A New Circuit for Communication Using Solitons," in *1995 Proc. IEEE Workshop on Nonlinear Signal and Image Processing*, June 1995.
- [20] A.V. Oppenheim, K.M. Cuomo, R.J. Barron, and A.E. Freedman, "Channel Equalization for Communication with Chaotic Signals," in *Proc. The 3rd Technical Conference on Nonlinear Dynamics (CHAOS) and Full Spectrum Processing*, July 1995.
- [21] G.W. Wornell, "Efficient Multiuser Communication in the Presence of Fading," in *Proc. IEEE Int. Sympo. Inform. Theory*, (Whistler, Canada), Sept. 1995. (long presentation)
- [22] G.W. Wornell and Mitchell D. Trott, "Signal Processing Techniques for Efficient use of Diversity in Wireless Communications," to appear in *ICASSP 1996*, Atlanta, GA, May 7-10, 1996.
- [23] H.C. Papadopolous and G.W. Wornell, "A Class of Stochastic Resonance Systems for Signal Processing Applications," to appear in *ICASSP 1996*, Atlanta, GA, May 7-10, 1996.
- [24] K.M. Cuomo, A.V. Oppenheim and R.J. Barron, "Channel Equalization for Self-Synchronizing Chaotic Systems," to appear in *ICASSP 1996*, Atlanta, GA, May 7-10, 1996.
- [25] W. Lam and G.W. Wornell, "Multiscale Analysis of Fractal Point Processes and Queues," to appear in *ICASSP 1996*, Atlanta GA, May 7-10, 1996.

2.4 Technical Reports

- [1] G.W. Wornell, "Synthesis, Analysis, and Processing of Fractal Signals", RLE Tech. Rep. No. 566, Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA 02139; November, 1991.
- [2] K. Cuomo, A.V. Oppenheim and S. Isabelle, "Spread Spectrum Modulation and Signal Masking Using Synchronized Chaotic Systems", RLE Tech. Rep. No. 570, Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA 02139; April, 1992.
- [3] K.M. Cuomo and A.V. Oppenheim, "Synchronized Chaotic Circuits and Systems for Communications," RLE Tech. Rep. No. 575, M.I.T., Cambridge, MA, December 1992.
- [4] M.D. Richard, "Probabilistic State Estimation with Discrete-Time Chaotic Systems", RLE Tech. Rep. No. 571, Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA 02139; May, 1992.
- [5] Kevin M. Cuomo, "Analysis and Synthesis of Self-Synchronizing Chaotic Systems," RLE Tech. Rep. No. 582, M.I.T., February 1994.
- [6] Michael D. Richard, "Estimation and Detection with Chaotic Systems," RLE Tech. Rep. No. 581, M.I.T., February 1994.

- [7] Kambiz C. Zangi, "Optimal Feedback Control Formulation of the Active Noise Cancellation Problem: Pointwise and Distributed", RLE Tech. Rep. No. 583, M.I.T., May 1994.
- [8] Gregory W. Wornell, "Efficient Symbol-Spreading Strategies for Wireless Communication," RLE Tech. Rep. No. 587, M.I.T., October 1994.
- [9] Steven H. Isabelle, "A Signal Processing Framework for the Analysis and Application of Chaotic System," RLE Tech. Rep. No. 593, M.I.T., May 1995.

2.5 Doctoral Theses

- [1] G.W. Wornell, "Synthesis, Analysis, and Processing of Fractal Signals", PhD Thesis, Massachusetts Institute of Technology, September, 1991.
- [2] Kevin M. Cuomo, "Analysis and Synthesis of Self-Synchronizing Chaotic Systems," PhD Thesis, Massachusetts Institute of Technology, Dec. 1993.
- [3] Michael D. Richard, "Estimation and Detection with Chaotic Systems," PhD Thesis, Massachusetts Institute of Technology, Nov. 1993.
- [4] Kambiz C. Zangi, "Optimal Feedback Control Formulation of the Active Noise Cancellation Problem: Pointwise and Distributed", PhD Thesis, Massachusetts Institute of Technology, Feb. 1994.
- [5] Steven H. Isabelle, "A Signal Processing Framework for the Analysis and Application of Chaotic System," PhD Thesis, Massachusetts Institute of Technology, Feb. 1995.

2.6 Masters' Theses

- [1] John R. Buck, *Implementation and Evaluation of a Dual-Sensor, Time-Adaptive EM Algorithm for Signal Enhancement*, S.M., August, 1991.
- [2] Andrew C. Singer, *Codebook Prediction*, S.M., Massachusetts Institute of Technology, January 1992.
- [3] Warren M. Lam, *Wavelet Based Representations and Algorithms for Generalized Fractal Signals*, S.M. Thesis, Massachusetts Institute of Technology, August 1992.
- [4] Haralabos Papadopoulos, *Detection and Estimation of a Class of Chaotic Signals with Application to Communications*, M.S. Thesis, Massachusetts Institute of Technology, May 1993.
- [5] Brian M. Perreault, *A Single Sensor Control Algorithm for Active Noise Cancellation*, S.M. Thesis, September 1993.
- [6] Stanley W. Brown, *A Feasibility Analysis of Single-Sensor Active Noise Cancellation in the Interior of an Automobile*, S.M. Thesis, Massachusetts Institute of Technology, June 1995.
- [7] Alan Freedman, *Transmission Channel Compensation in Self-Synchronizing Chaotic Systems* M.Eng. Thesis, Massachusetts Institute of Technology, June 1995.

3 Patent Disclosures

- [1] E. Weinstein, M. Feder and A.V. Oppenheim, "Multi-Channel Signal Separation", U.S. Patent Number 5,208,786, Issued May 1993.
- [2] Gregory W. Wornell and Alan V. Oppenheim, "Communication System Utilizing Self-Similar Signals," U.S. Patent Number 5,285,478, Issued February 1994.
- [3] Kevin M. Cuomo and Alan V. Oppenheim, "Communication Using Synchronized Chaotic Systems," U.S. Patent Number 5,291,555, Issued March 1994.
- [4] Alan V. Oppenheim, Ehud Weinstein, Kambiz Zangi and Meir Feder, "Active Noise Reducing," U.S. Patent Number 5,293,525, Issued March 1994.

3.1 Patent Application Filed

- [1] A.V. Oppenheim and K. Zangi, "Optimal Feedback Control Active Noise Cancellation".